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14. ABSTRACT

The primary objectives of this project were to develop new real-time algorithms for adaptive filtering and system identification, and to apply these algorithms in new methods for optics and target tracking. Mathematical analysis of the performance of the adaptive algorithms in the presence or unmodeled noise also was an important part of the project. The research was aimed at supporting research at the Air Force Research Laboratory on directed energy weapons. Additional application areas included optical communication systems, blind identification and deconvolution, active control of noise and vibration, and detection of damage in elastic structures. The primary application has been control of laser beams, with the objective of developing adaptive control algorithms that yield higher performance than existing methods for beam steering and adaptive optics.

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FINAL REPORT

AFOSR GRANTS F-49620-00-1-0156 and F-49620-02-1-0156

ADAPTIVE FILTERING, IDENTIFICATION, AND CONTROL WITH APPLICATIONS TO ADAPTIVE OPTICS

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Abstract

The primary objectives of this project were to develop new real-time algorithms for adaptive filtering and system identification, and to apply these algorithms in new methods for optics and target tracking. Mathematical analysis of the performance of the adaptive algorithms in the presence or unmodeled noise also was an important part of the project. The research was aimed at supporting research at the Air Force Research Laboratory on directed energy weapons. Additional application areas included optical communication systems, blind identification and deconvolution, active control of noise and vibration, and detection of damage in elastic structures. The primary application has been control of laser beams, with the objective of developing adaptive control algorithms that yield higher performance than existing methods for beam steering and adaptive optics.

Adaptive Optics

In adaptive optics (AO), deformable mirrors are driven by active control loops that feedback wave front sensor measurements to compensate for turbulence-induced phase distortion of optical waves propagating through the atmosphere. The control loops in classical AO systems are not truly adaptive, since they have fixed gains based on assumed statistics of atmospheric turbulence. Adaptive compensation is needed in many AO applications because wind velocities and the strength of atmospheric turbulence can change rapidly, rendering classical AO loops far from optimal. Under the current grant, adaptive wavefront reconstruction algorithms based on recursive least-squares (RLS) estimation of optimal reconstructor matrices have been introduced. In this approach, an adaptive control loop augments a classical AO feedback loop. Simulation results have shown that the adaptive loops developed in this research are robust with respect to modeling errors and sensor noise.

A well-chosen parameterization of actuator and sensor spaces is essential to the development of a computationally tractable and effective adaptive control loop in adaptive optics. We have developed various parameterizations of actuator space. One of the main accomplishments under this grant

During the first two years of the grant, we concentrated primarily on adaptive optics for relatively thin turbulence paths. Such problems, represented in Figure 1, arise mainly in astronomy and tracking satellites or other vehicles traveling above the atmosphere. During the third year, we began investigating adaptive optics problems for long turbulence paths, concentrating on examples representative of applications in laser weapons such as ABL, represented in Figure 2. These problems are more challenging for the adaptive filters in our control algorithms because of the broader bandwidth of the disturbance that the extended atmospheric turbulence produces in optical wave fronts. However, the combination of improved filtering methods and novel applications of system identification are beginning to produce encouraging results.

Until recently, this project has involved theoretical analysis, development of real-time algorithms for adaptive filtering and control, and numerical simulations. This spring, we were awarded a DURIP grant through AFOSR that will allow us to perform experimental research on adaptive optics at UCLA. Currently, we are assembling the experimental equipment, and we expect to have AO experiments working by the end of the year.

A second major effort during the past year has concerned real-time system identification. In this effort, adaptive filters are used for two types of identification problems: identification of unknown and time-varying plants to be controlled or monitored, and adaptive identification of unknown or changing disturbance characteristics. Most system identification algorithms are implemented off-line, but methods based on adaptive filtering can be implemented on-line, in real time. Our recent research has dealt with subspace methods for system identification. The development of subspace algorithms based on adaptive filters is continuing, along with the application of these algorithms to adaptive optics.

Some of our main accomplishments in adaptive optics during concern problems for long turbulence paths, concentrating on examples representative of applications in laser weapons such as ABL, represented in Figure 2. The very broad-band nature of the turbulence-induced phase distortions in optical waves propagating through extended turbulence presents a difficult challenge for the multichannel adaptive filter in our adaptive control loops for adaptive optics, shown in Figure 3. By combining new methods for selecting control and sensor channels for the adaptive filter with on-line system identification, we have been able to develop new AO control loops with reduced numbers of channels that produce significant wave front prediction in simulations for strong turbulence and long turbulence paths.

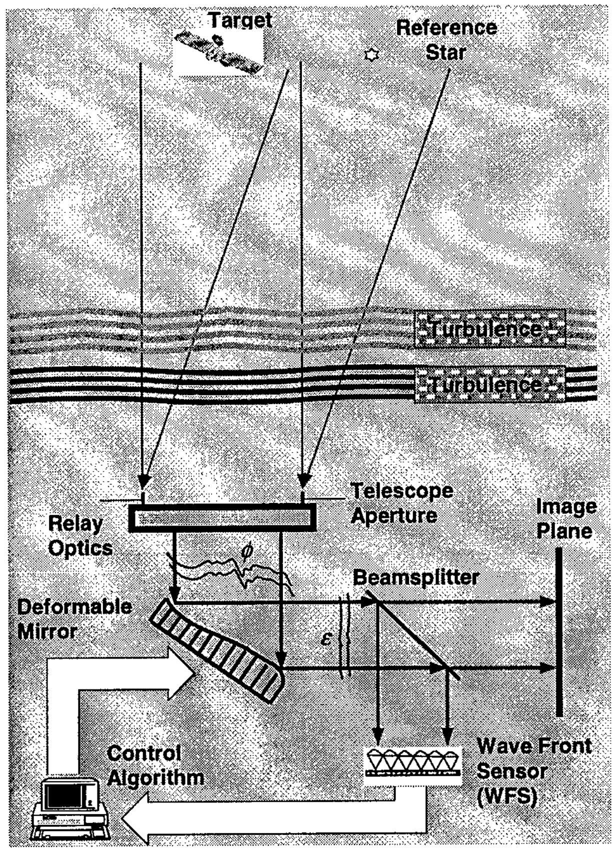


Figure 1: An adaptive optics problem for astronomy and satellite tracking.

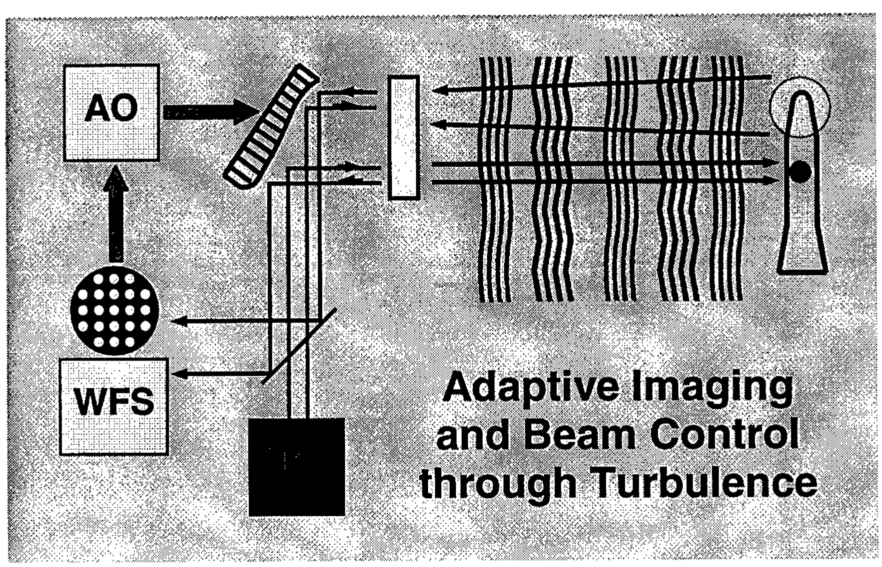


Figure 2: An adaptive optics (AO) problem for target tracking and beam control in laser weapons. WFS: wave front sensor. HEL: high-energy laser.

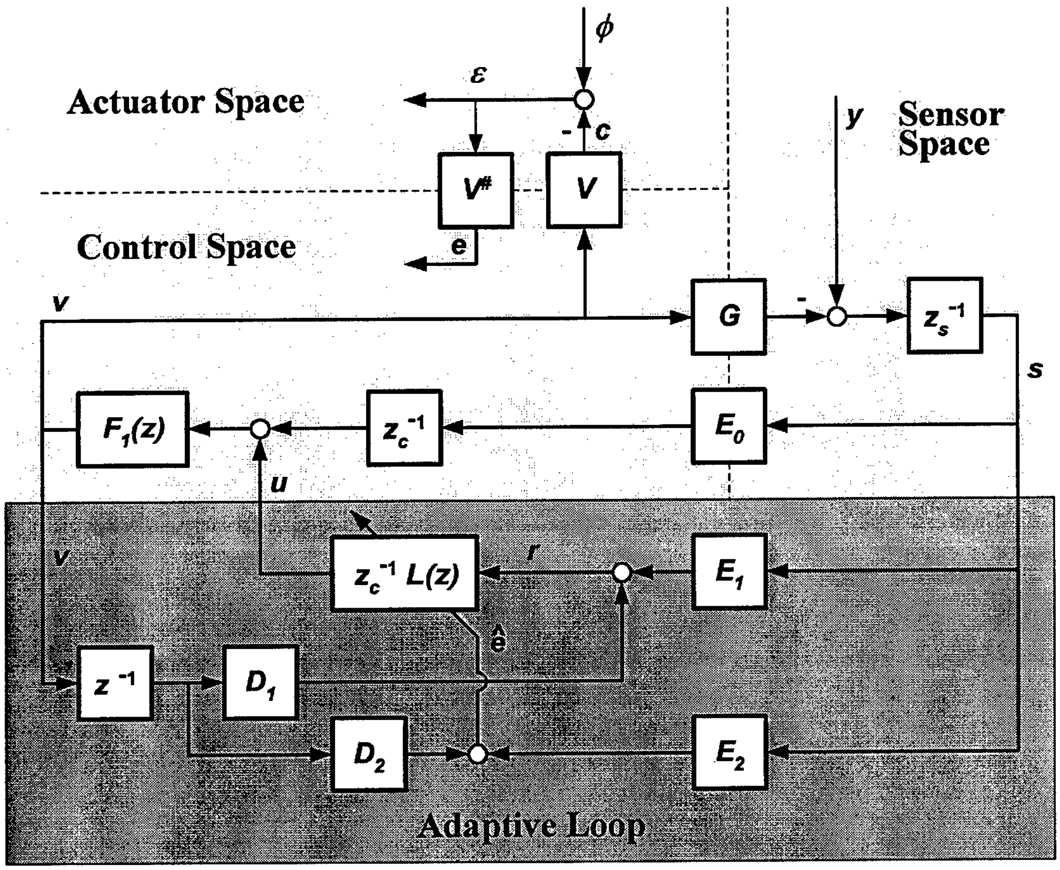


Figure 3: Block diagram for adaptive optics. The adaptive lattice filter chooses *L(z)* to minimize the variance of the wave front error.

Beam Control Experiment

Recently, we have applied subspace system identification and lattice-filter based adaptive control algorithms to a beam steering experiment at UCLA. This work is continuing, but already it has demonstrated the enhanced disturbance rejection achievable in laser beam steering by modern optimal feedback controllers augmented by adaptive control loops that determine control gains that are optimal for the current disturbance acting on the laser beam. In our adaptive loops, an adaptive lattice filter implicitly identifies the disturbance statistics from real time quad cell data.

Figure 4 shows our current beam-steering experiment, in which we apply both an H_∞ feedback control loop and an adaptive control loop to reject disturbance added to the direction of a laser beam. Figure 5 shows sample trajectories of the centroid of the image of the laser beam on the quad cell in the experiment. These results demonstrate the enhanced beam control possible with our adaptive control schemes. Papers reporting our results on this beam steering experiment are being prepared.

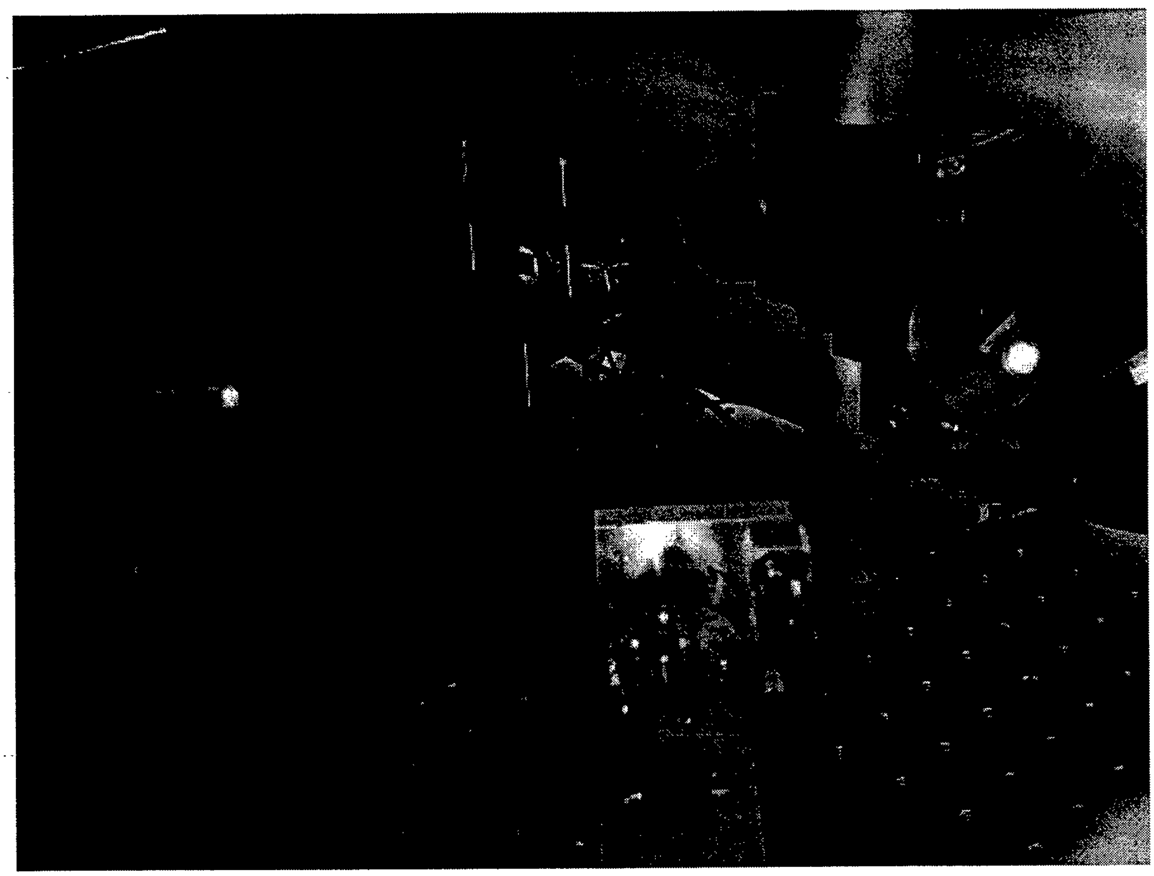
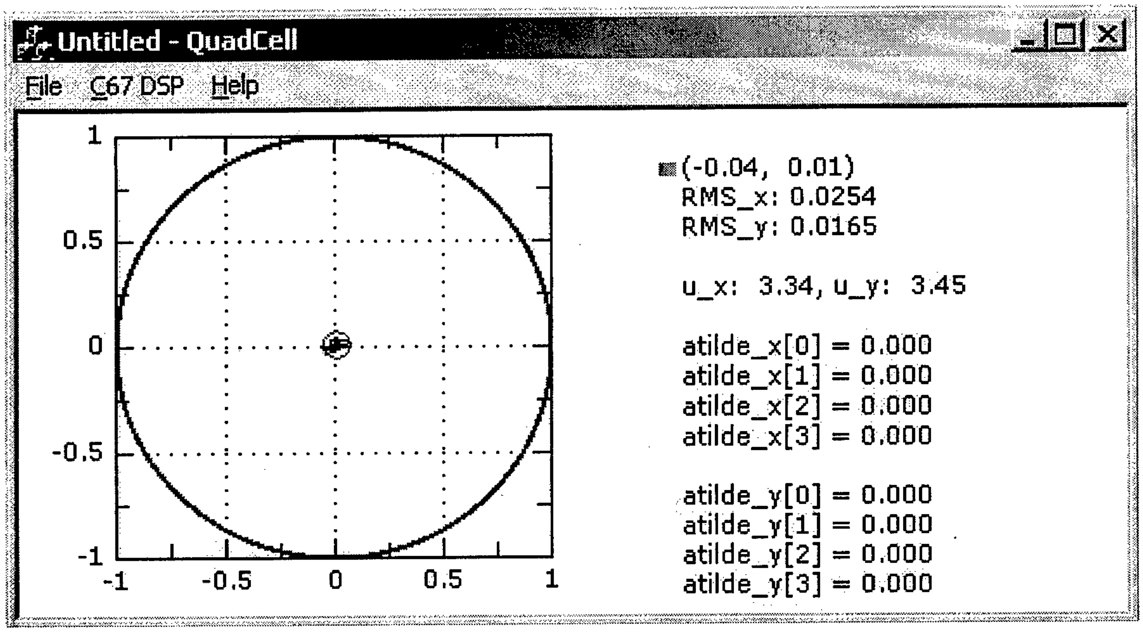


Figure 4. UCLA adaptive beam steering experiment. The laser beam leaves the source on the right side in the picture, reflects off beam steering mirror 1 (the control actuator), then reflects off beam steering mirror 2 (the disturbance actuator, left side in the picture), and finally hits the quad cell in the top of the picture.



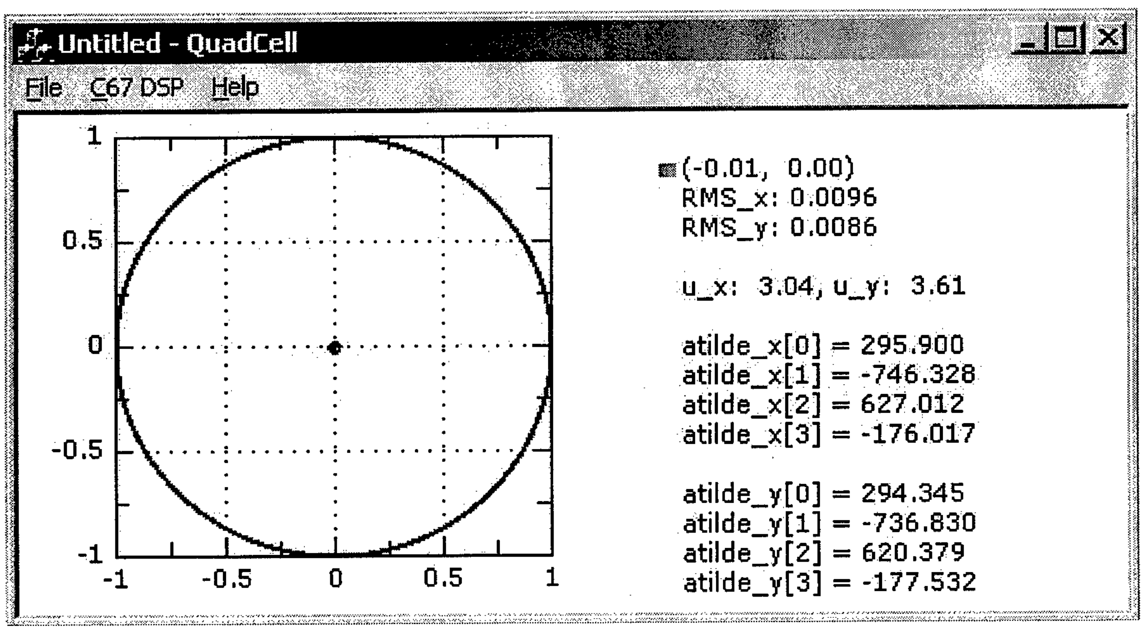


Figure 5. Trajectories of the laser beam image on the quad cell. Top: With H_∞ feedback loop only. Bottom: Feedback loop augmented by adaptive control loop (atilde = adaptive controller gains).

System Identification

A major effort under the grant concerned on real-time system identification. In this effort, adaptive filters were used for two types of identification problems: identification of unknown and time-varying plants to be controlled or monitored, and adaptive identification of unknown or changing disturbance characteristics. Most system identification algorithms are implemented off-line, but methods based on adaptive filtering can be implemented on-line, in real time. Our recent research has dealt with subspace methods for system identification. The development of subspace algorithms based on adaptive filters is continuing, along with the application of these algorithms to adaptive optics.

Our recent research at UCLA has produced a new class of subspace algorithms for system identification. In our approach, which is illustrated in Figure 1 the projection of future data onto past data is performed by multichannel least-squares lattice filters with parameterizations and channel arrangements particularly suited to subspace system identification. Because adaptive lattice filters provide the core computational engine of our subspace system identification algorithms, the main computational burden of the algorithms can be executed in real time, as data is being sampled.
In a real-time adaptive implementation, the singular-value decomposition of the Hankel matrix and construction of the state-space system matrices are performed periodically, over a few seconds at most, depending on available computational power, while updating of the QR factorization of the data matrix continues in real time as new data is acquired.

In deriving our lattice-filter based subspace algorithms, we have developed a method for using our lattice filters to construct the triangular matrix R in the QR factorization of a Toeplitz data matrix W whose columns are shifted versions of the input and output data sequences. For subspace system identification, only this matrix R is needed. Although, it is generally understood among adaptive-filtering researchers that RLS lattice filters perform a block orthogonalization of the columns of the data matrix, this orthogonalization is only implicit and sometimes only approximate. Our class of RLS lattice filters are unique in that they perform a complete orthogonalization (not just a block orthogonalization) of the data matrix, and this orthogonalization is exact even for short data sequences because of the unwindowed initialization of our algorithms. However, even with our basic lattice filters, this orthogonalization is still implicit. Our procedure for constructing the R matrix for the QR factorization from the reflection coefficients and residual errors in the lattice filter is a recent discovery---which we believe is one of our most significant discoveries over the past few years. As far as we know, it has not been possible to construct such an R matrix with any previous lattice filters.

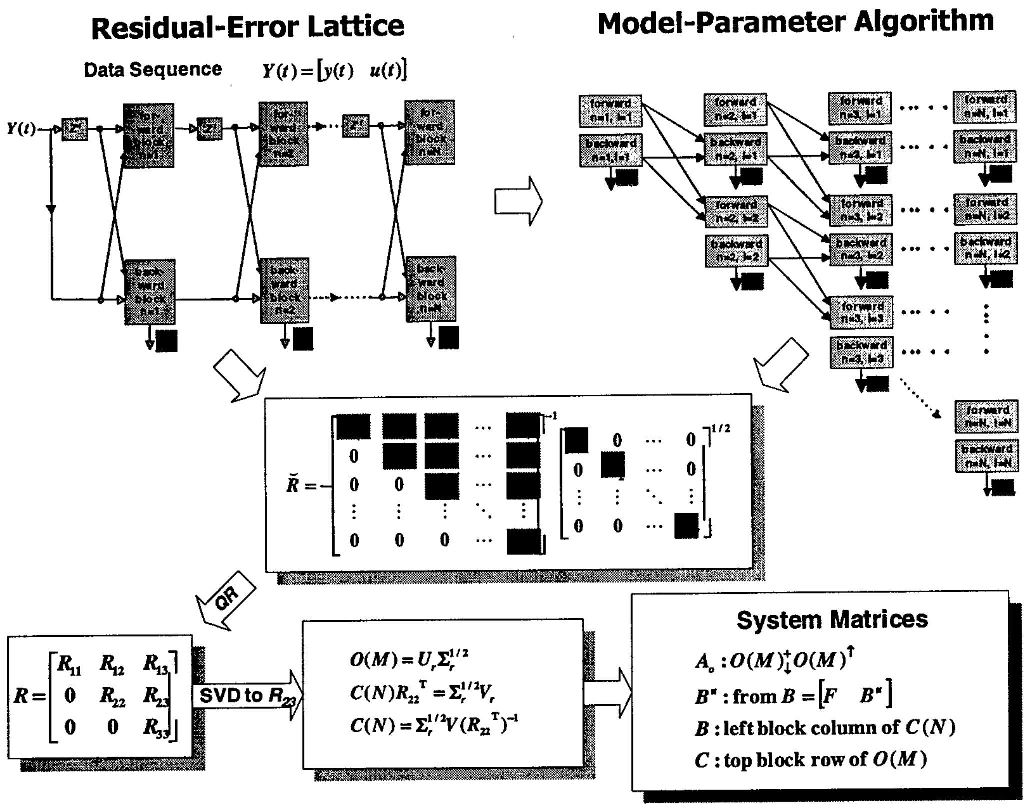


Figure 6. Subspace System Identification Based on Multichannel RLS Lattice Filter.

Damage Detection in Materials

During the past year, we have begun investigating the application of system identification to the detection of cracks—or other types of damage—in elastic structures like plates and beams. We have introduced two types of state-space system identification methods. In the first method, the appearance of a crack produces a transient dynamic response in the structure that can be modelled as an impulse response of the structure, with the nature of the impulse dependent on the location and nature of the crack. In the system identification method, the system is excited for a short time with a known broad-band input sequence. In both cases, the structure is instrumented with an array of sensors to detect propagating waves, and a state-space model is identified from the input-output data. The location of the crack relative to the sensor array is embedded in the matrices of the identified state-space model. Our first results with this approach to damage detection were reported in [10], and additional papers are in preparation.

Personnel Supported

Faculty: J. S. Gibson
Graduate Students: Chi-Chao Chang, Neil Chen, Yu-Tai Liu, Nestor Perez
Post Doctoral Scholar: Neil Chen

Interactions

J. S. Gibson has collaborated regularly throughout the past year on adaptive optics for ABL with Dr. Don Washburn (505-846-1597) of the Air Force Research Laboratory at Kirtland AFB.

J. S. Gibson has consulted with Dr. Ben G. Fitzpatrick (310-216-1677) of Tempest Technologies, Los Angeles, CA, on image tracking and filtering for ABL. Current efforts are aimed at developing algorithms for tracking missile images propagating through atmospheric turbulence, and applying new adaptive optics control loops in laboratory experiments.

Transitions

J. S. Gibson collaborated on adaptive optics for ABL with Dr. Don Washburn (505-846-1597) and Captain Matthew Whiteley of the Air Force Research Laboratory at Kirtland AFB, September 1990, December 1990, March 1990, May 1990.

J. S. Gibson has consulted with Dr. Ben G. Fitzpatrick (310-216-1677) of Tempest Technologies, Marina del Rey, CA, on image tracking and filtering for ABL. Current efforts are aimed at developing algorithms for tracking missile images propagating through atmospheric turbulence.

CSA Engineering, Inc in Albuquerque, NM, has an AFRL SBIR (Phase II) contract for "Improved adaptive reconstructor algorithm performance using field programmable gate arrays." This project will produce a real-time hardware implementation (FPGA) of an adaptive controller for adaptive optics that is based in large part on the two main features of the adaptive control loops developed under this grant: (1) the use of an adaptive filter for wave front prediction and reconstruction, and (2) a reparameterization of actuator and sensor spaces that decouples control channels and achieves beneficial spatial filtering.

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[1] Chi-Chao Chang, "Adaptive Optics: Wavefront Reconstruction by Adaptive Filtering Control," Ph. D. Dissertation, UCLA, 2000.

[2] C.-C. Chang and J. S. Gibson, "Parallel Control Loops Based on Spatial Subband Processing for Adaptive Optics," American Control Conference, (Chicago, Illinois), June 2000.

[3] J. S. Gibson, C.-C. Chang, and B. L. Ellerbroek, "Adaptive Optics: Wavefront Correction by Use of Adaptive Filtering and Control," *Applied Optics, Optical Technology and Biomedical Optics*, Vol. 39, No. 16, June 2000, pp. 2525–2538.

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[9] R. T. M'Closkey, J. S. Gibson, and J. Hui, "System Identification of a MEMS Gyroscope," *ASME Journal of Dynamic Systems, Measurement, and Control*, Vol. 123, No. 2, June 2001, pp. 201–210.

[10] A. K. Mal, F. Ricci, S. Gibson, S. Banerjee, "Damage Detection in Structures from Vibration and Wave Propagation Data," SPIE International Symposium on Smart Structures and Materials, San Diego, CA, March 2003.